Atmospheric and Surface Backscatter: Dynamic Range and Spatial Variability Effects on Lidar Design and Performance

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Abstract—Although nearly all the airborne and orbiting active laser sensors to date have operated at near nadir pointing angles, in either lidar or altimeter mode, we anticipate dual-mode instruments such as GLAS to emerge and impact the remote sensing community in the next decade. We discuss the variability which off-nadir scanning brings to the measurement concepts – variability which can engender new measurement capabilities as well as cause interpretational problems. In that context we discuss the dynamic range of surface reflectance (backscatter) over water and various land surfaces, including dependence on nadir angle. A new measurement opportunity which exists using scanning lidar systems optimized for wide dynamic range is the measurement of surface wind over oceans.

1. Introduction

In this paper we discuss certain characteristics of the sources of backscatter in airborne and space lidars or laser altimeters which impact the design and data analysis approaches. In the future are opportunities for lidar and altimeter instruments, which in the past have been designed and used for clearly separate sets of objectives, to merge into more multi-functional instruments which have a wider range of measurement capabilities. The NASA GLAS (Geoscience Laser Altimeter System) instrument is an example in the near future. A step beyond would be a scanning instrument with somewhat larger energy-aperture product – an instrument which could include a Doppler or DIAL measurement receiver in addition to the backscatter measurement capability. Scanning lidars bring about opportunities for improved complementarity with other sensors in a sensor suite. For the case of Doppler wind lidar, off-nadir scanning is essential. The enhanced measurement capability brought about by scanning also merits careful consideration of data interpretation issues and means of dealing with those issues with hardware and/or data processing software flexibility.

2. Scales of Backscatter Magnitude and Spatial Homogeneity in the Atmosphere

It is important to recognize the various cloud and aerosol scales of homogeneity and the potential impacts of inhomogeneities on lidar measurement biases. Most lidar measurement applications rely on the ability to recognize cloud contributions to the backscatter signals and treat them properly. Examples of potential biases include overestimation of aerosol scattering due to misinterpretations in separating thin or scattered clouds from aerosol, biases in location assignments of wind speed (in Doppler lidar), and biases in location and/or concentration of species populations (in DIAL) due to multi-pulse averaging in the presence of clouds with structure at scales smaller than the averaging scale.

Earth orbiting lidar experiment designers must employ hardware and algorithm design approaches to minimize biases due to spatial inhomogeneities particularly when thin and/or scattered clouds are in the measurement volume. Figure 1 depicts scales of horizontal inhomogeneity (dimensions over which significant variations in scattering properties can occur) for various backscatter sources, based on data obtained from the NASA GSFC airborne backscatter lidar during the GLOBE missions [1] and from the LITE shuttle lidar experiment, managed by NASA LaRC [2]. The wide variety of cloud types are lumped together here, and the scale of inhomogeneity is essentially at the limit of the lidar measurement resolution – for the multi-pulse 1-second averaged profile data provided from the GLOBE lidar and for the lidar footprint in the case of LITE. The backscatter scale assumes a 100-m line-of-sight resolution, for ease of comparison with surface backscatter values to be presented. It is obvious that the potential exists for overlap in backscatter magnitude from cloud structures in the neighborhood of boundary layer aerosol or elevated aerosol layers in the free troposphere.

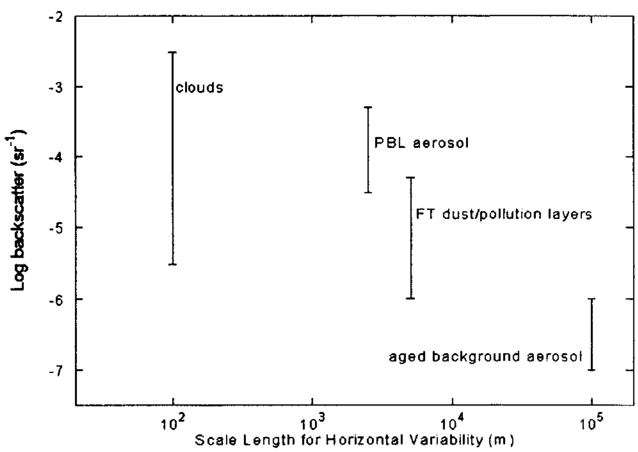

Figure 1. Range of backscatter level at 1.06-µm wavelength vs. minimum scale length of horizontal variability for various atmospheric backscatter sources (100-m line-of-sight path length assumed).

Spatial structure can usually be used as a tool to discriminate thin or small, scattered clouds in the lidar field-of-view, and in the case of future scanning lidars operating from Earth orbit, high vertical resolution and sufficient sensitivity will be critical. In the case of nadir-pointed lidars both vertical and horizontal structural information is used to discriminate. The horizontal dimension is useful for discrimination if several lidar profile samples are contained within the smallest scale of significant inhomogeneity for the aerosol, and the assumption of horizontal homogeneity of the aerosol layers can be invoked. However the future deployment of scanning lidars, with attendant sparse sampling in the horizontal, will demand greater attention to line-of-sight resolution in order to discriminate and isolate cloud contributions to the backscatter profile. If aerosol layer structure exists in the horizontal dimension at the 5 km scale, for example, the lidar sampling should be at least twice this spatial frequency of fluctuation, preferably more. Feasible scanning lidars will likely have footprint spacings larger than this. Analysis of single pulse data using line-of-sight (LOS) resolution of 100-m or less should permit detection/ discrimination and sufficiently accurate altitude assignment of cloud contributions to the measurement.

3. OCEAN SURFACE BACKSCATTER CHARACTERISTICS

The optical reflectance properties of the capillary and capillary-gravity waves on the ocean surface at low surface wind speeds can be modeled as an ensemble of tilted facets with a slope distribution dependent on the wind speed. The reflectance characteristics depart significantly from those of the ideal diffuse Lambertian surface, falling off much more rapidly with increasing nadir angle. At higher surface wind speeds the contributions from foam (whitecaps, *etc.*) and spray alter the angular reflectance properties. In the mid-visible, subsurface scattering will also contribute to the total reflectance, becoming dominant at larger off-nadir angles when foam is absent or nearly absent. In Figure 2 are modeled lidar reflectance plots for several values of surface wind speed, over a range of nadir angles appropriate to a scanning lidar case. This model was applied to data taken over ocean surfaces during the LITE mission in September, 1994 [3], using a controlled Shuttle tilt maneuver. Figure 2 applies to the Nd:YAG 1064-nm transmitted wavelength. The change in character of the 10 m/s curve at about 25° nadir angle to a flatter, more Lambertian dependence, occurs when foam begins to dominate the backscattering. At 10 m/s surface wind speed the assumed fractional coverage of foam is 1 %.

Comparing Figures 1 and 2 one can observe that at nadir angles beyond 20° the relatively calm ocean surface backscatter may be less than that from the boundary layer aerosol when a 100-m or larger LOS resolution is selected. This has obvious implications when the surface return is used for calibration of altitude or pointing angle.

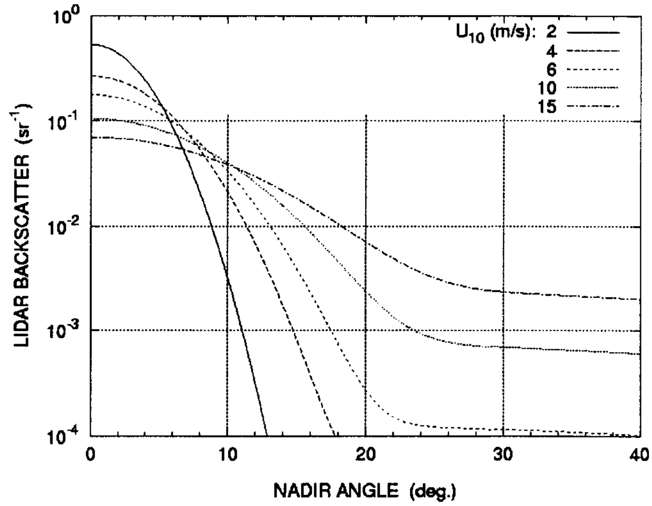

Figure 2. Modeled lidar reflectance from the sea surface for selected wind speeds. Subsurface volume backscatter is neglected.

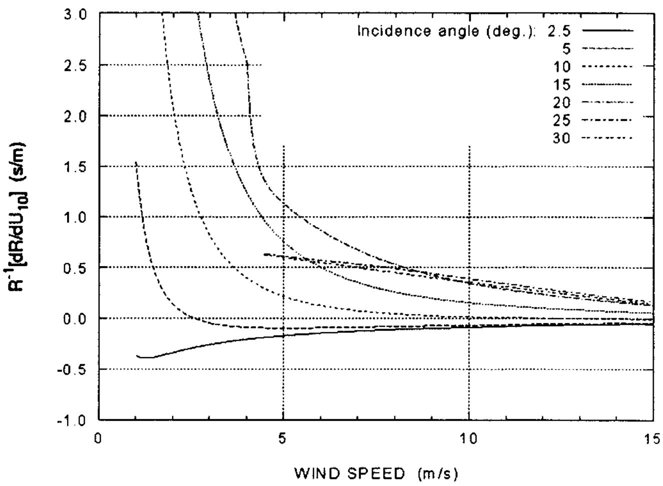

Figure 3. Lidar fractional reflectance increment with respect to incremental change in wind speed for selected nadir angles.

The ocean surface reflectance characteristics permit the possibility of using lidar for measurements of surface wind, analogous to the microwave scatterometer. The lidar applicability would obviously be in cases of clear atmosphere or conditions of scattered cloudiness. Figure 3 can be used in a sensitivity study, indicating which nadir angles would be best suited to surface wind speed measurements. Nadir angles of 15-20° are more sensitive to the wind speed effects over a wide range. The LOS range resolution capability must be considered in order to push the technique into the low surface wind speed regime.

4. LAND SURFACE REFLECTANCE CHARACTERISTICS

Land surface reflectance properties comprise a richly varied set of spectral and bidirectional characteristics. High spectral resolution datasets should be the resource of choice for lidar experiment planning. Data from many spectral radiometers and imaging spectrometers contain inherent spectral averages over atmospheric absorption lines as well as some surface spectral features. AVIRIS (Airborne Visible-Infrared Imaging Spectrometer) is a relatively high resolution (10 nm FWHM) imaging spectrometer instrument [4] which, when combined with careful analysis of atmospheric effects, produces spectral reflectance datasets which are useful for lidar analyses. AVIRIS has been used for surface mineralogy studies, soil characterization, vegetation classifications, and forest characterizations as examples. Although the land surface types seem myriad, the dynamic range of natural reflectance is about two orders of magnitude, far less than the dynamic range of atmospheric cloud and aerosol backscatter.

When modeling lidar backscatter, one must avoid the temptation to commonly assume a Lambertian description for a particular surface, with reflectance equal to a value obtained using an angle-integrating instrument. Bidirectional reflectances of many materials are asymmetric in the forward vs. backward scattering directions, and some feature a specular peak. Of particular importance to lidar is the fact that many land surface materials exhibit an enhanced reflection in the direction of the illumination, *i.e.*, a retroreflection enhancement, or "opposition effect" [5-7]. The bidirectional reflectance characteristics of a variety of land surface types will receive much more attention in the near future with the MISR (Multiangle Imaging SpectroRadiometer) instrument in the NASA Earth-orbiting Terra spacecraft payload [8].

5. CONCLUSIONS

Two lidar developments which will bring about increased flexibility and more diversified utilization of the lidar resources are a multi-functional receiver tailored for both atmospheric and surface measurements (*e.g.*, altimetry) and an off-nadir scanning capability. The off-nadir scanning capability potentially improves the complementarity with other sensors in the same payload or on other platforms. One example of a new measurement product which could derive from scanning is surface wind speed over ocean surfaces. This would complement the measurement of marine boundary layer structure either from Doppler lidar profiling or from backscatter lidar profiling.

The characteristics of the sources of lidar backscatter impact the experiment design approaches. When designing airborne and Earth orbiting lidar experiments and accompanying data interpretation algorithms, careful attention should be given to the wide range of variability of backscatter magnitude as well as spatial scales of inhomogeneity. The potential for susceptibility to measurement biases due to inadequate assignment of cloud effects, for example, should be an important factor to consider when engaged in tradeoffs of energy-aperture products, pulse-repetition-frequencies, and LOS resolution. These considerations are likely to be even more important with scanning lidar designs which sample over swath widths of a few hundred km.

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